An Evolutionary Picture for Quantum Physics

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Dedicated to the memory of Misha Polivanov
who strove to conserve a cultural heritage in
dark times

Abstract

In the orthodox language of Quantum Mechanics the observer occupies a central position and the only "real events" are the measuring results. We argue here that this narrow view is not forced upon us by the lessons of Quantum Physics. An alternative language, closer to the intuitive picture of the working physicist in many areas, is not only possible but warranted. It needs, however, a different conceptual picture ultimately implying also a different mathematical structure. Only a rudimentary outline of this picture will be attempted here. The importance of idealizations, unavoidable in any scheme, is emphasized. A brief discussion of the EPR-phenomenon is added.

1 Language and philosophical extrapolations

Prominent in the vocabulary of Quantum Theory are the words "physics systems", "state", "observable", "measuring result". The general theory tells us how these terms are represented in the mathematical scheme and it tells us the following: *If a system S is in a state s and we measure the observable A then the probability of obtaining the result a is given by the formula* $p = \mathrm{tr}sP_a^{(A)}$. I shall not explain the formula since you know it all.

This language has proved to be very efficient in a wide area. Nevertheless we should not consider it as sacrosanct. There are limits to its usefulness and every word in the vocabulary is subject to criticism.

Let us start with the word "observable". It suggests that there is an observer. Does this have to be human being? Certainly in the discussions of the early days of Quantum Mechanics no other interpretation was intended. One of the concerns of Niels Bohr was epistemology i.e. the question of what we (humans) can know and how we can communicate. But even if we want to understand the word observer in a wider sense we must endow him at least with the faculties of consciousness, intelligence in planning and free will in execution. So there is the question: does Quantum Physics force us to abandon the old picture of a real outside world, called nature, which exists separate from our consciousness? Do the finding of atomic physics decide in favour of some philosophical system like positivism or idealism in contrast to realism? I do not think so. The raw material of physics, which the theory is supposed to explain, consists of facts

which can be documented. Nobody claims that in the recognition of a dot on a photographic plate or of the print out of a computer the quantum mechanical uncertainties play any role. What is often claimed is that documents are necessarily macroscopic and that amplification to the macroscopic scale is essential for the creation of a fact. We shall look at this important point carefully below. It has, however, no bearing on the question about the role of the mind in the interpretation. No matter what our ultimate philosophical beliefs are, physics by its very method proceeds from an *"as if"* realism. Thus one can hardly doubt that facts similar to measuring results occur in nature irrespective of whether they arise in a planned experiment and enter the consciousness of an observer. For instance we believe that cosmic rays passing through a body of water which happens to be at the boiling point may produce lines of vapour bubbles. A child passing by may wonder about this phenomenon but probably not even notice it. Thus we may assume that a measuring result is an event whose reality status is no better than that of other events in nature.

Granting this we must ask: what constitutes an event in the above example? There are bubbles marking approximate points in space-time and we attribute these to an elementary quantum process such as

$$\mu + \text{ atom } \rightarrow \mu + \text{ ion } + e + \gamma \tag{1}$$

which creates a localized disturbance in the superheated liquid and this in turn acts as a germ of vaporization. Can we separate the elementary process (1) as a closed process from the subsequent macroscopic amplification? What if the temperature of the water was a few degrees lower and no bubbles were formed? This brings us back to the question about the role of amplification. Clearly we have to distinguish between documents and facts. While the former are needed for the unequivocal establishment and communication of a result of observation i.e. are indispensable on the epistemological side we should recognize that physics transcends epistemology. In physics we try to extrapolate from what we know or even can know to form a coherent picture of the world using criteria like reasonableness, simplicity .... Observations are a tool and a check, not the ultimate purpose. The assumption of (1) as an individual fact is an idealization which has to be judged by its reasonableness.

2   Individuals and ensembles.

Niels Bohr is sometimes regarded as a crown witness for positivism: his emphasis on epistemology seems to provide some justification for this. But Bohr disclaimed such a label and reportedly felt unhappy about this misunderstanding of the message of Quantum Mechanics. Indeed in his writings you find no trace of a doubt about the real existence of electrons and atoms but only about our ability of assigning simple attributes to them. One central point of Bohr's argument is that Quantum Theory introduces a discrete element into physics which implies not only the stability of atoms but also the indivisibility of quantum processes whether it be a quantum jump in an atom or the passage of a particle between source and detector in the double slit experiment. Any subdivision of such a process, the attempt to describe it as a continuous development in space and time, cannot have an objective meaning. The Schrödinger equation does not describe the individual process. It describes the continuous change of probabilities for possible facts not the fact itself. Similarly the formulation of quantum mechanical statements quoted at the beginning, which is essentially due to von Neumann, refers to the statistical behavior in an ensemble: the individual fact, called "measuring result", remains unresolved. This calls attention to the division problem. What can be singled out as

an individual? This question applies in parallel to matter and to events. To say that matter is composed of atoms and an atom is composed of electrons, protons and neutrons is obviously a coarse picture. The Pauli principle implies that the "constituents" cannot be regarded as individuals and even where this principle does not enter, e.g. in the case of the hydrogen atom, the composition picture is only an analogy providing a useful model for approximations. An individual part of matter becomes precisely defined only as an asymptotic notion which can be arbitrarily well approximated by isolation. The simplest such individuals are particles (including stable, compact objects like a crystal). Their internal structure is rigidly fixed by (quantum) laws of nature. Similarly an individual event is an asymptotic notion. The simplest type of event is a collision process between particles, well isolated from other matter and closed by the spatial separation of the reaction products. Its mental decomposition into subevents or "virtual events" (as in Quantum Field Theory) is a useful model but no individual existence of the virtual events can be claimed. This hinging of basic concepts to asymptotic situations which are only approximately realizable emphasizes the need for idealizations. Idealizations cannot be avoided if we want to talk about any subdivision of the universe [1] though this does not necessarily have to be done in terms of particles and collisions. Considering for instance the regime of an extended medium of high density we may define an individual event as a significant deviation from local equilibrium. In the orthodox interpretation the idealization begins with the cut between the "quantum system" and the observing instruments described classically and continues with Bohr's effort to define a "closed quantum process" as a complete description of the experimental arrangement, a task which demands judicious judgment as to what is relevant and what is not. This is well adapted to laboratory situations when we have to consider both articles and macroscopic hardware. But it leaves open the task of translating a description of the apparatus into the mathematical representatives of the state prepared and the observable measured and it does not answer the question of why the interaction between apparatus and quantum system leads in each individual case to a "measuring result". Again the occurance of such events has to be postulated. The attempt to explain this as a consequence of the formalism in the theory of measurement, for instance by the study of decoherence, goes only part of the way (see below).

So far our only change from the orthodox view has been to replace the notion of "measuring result" by the more general notion of an "event" which is considered as a fact independent of the presence of an observer. This has, however, important consequences. An event is irreversible. It is the transition from a possibility to a fact. We are raised in the belief that the fundamental laws do not stipulate an arrow of time but are invariant under time reversal. The explanation of the manifest irreversibility of processes around us is delegated to statistical mechanics which, starting from fundamental laws invariant under time reversal, arrives at irreversible behaviour in the macroscopic domain [2]. If we believe that this is the only mechanism by which irreversibility

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[1] John Bell's quest for "beables" which can be precisely defined under any circumstances and his criticism of Quantum Theory on the grounds that it is not enough to achieve agreement with experiments "for all practical purposes" (FAPP) disregards the possibility that with increasing insistence on precision the subdivision of the universe must become necessarily coarser and the description less detailed.

[2] The miracle by which this is achieved is the following. Going over to a "coarse grained" description one finds that different macroscopic states have very different statistical weights. Starting with a state of low weight it is therefore overwhelmingly probable that later on it develops into a state of higher weight. There remains the question of why we only want to draw conclusions from a given situation at an earlier time to that at later times and not vice versa and why we usually encounter the situation that at the early time the state has low statistical weight. In a laboratory situation the latter circumstance can be attributed to the experimenter starting his investigation. On the larger scale it must be blamed ultimately on cosmology telling us that observed large deviations from equilibrium did not arise from an earlier situation closer to equilibrium as a consequence of a

can arise we must conclude that the elementary process, even if isolated, cannot be regarded as real but needs the macroscopic amplification before we can talk about a fact. This argument has played a role in many discussions of the quantum mechanical measuring process. Niels Bohr refers to it in rather careful and slightly enigmatic formulations, for instance: "Far from implying a special difficulty, the irreversible amplification effects on which the registration of atomic objects depends remind us of the *essential irreversibility inherent in the concept of observation*". Now, if we do not want to place the concept of observation into the center of physics, we must ask ourselves: what would be the natural picture if we claim that there are discrete, real events on any scale?

Starting from this idea we come almost unavoidably to an evolutionary picture of physics. There is an evolving pattern of events with causal links connecting them. At any stage the "past" consists of the part which has been realized, the "future" is open and allows possibilities for new events. Altogether we have a growing graph or, using another mathematical language, a growing category whose objects are events and whose (directed) arrows are the causal links. We assume further that the relation to space-time is provided by the events. Each event marks roughly a region in space-time, the sharpness of which depends on the nature of the event. No independent localization properties of links is assumed. The reason for this may be seen in the case of low density where the scheme can most easily be compared with the customary quantum theoretical description. In this case the causal links correspond to particles, the events to collision processes between them. To attribute localization to a particle between two processes would contradict basic experiences in Quantum Mechanics as emphasized by Bohr's concept of indivisibility and mathematically described by the spreading of the wave packet for the center of mass motion over a large volume. Thus, after the source event of emission we have roughly a spherical wave function. It should not be interpreted as relating to the probability for the changing position of a point-like particle but rather to the probability for the space-time location of the collision center in a subsequent event. Only after the realization of this target event we may (retrospectively) assign an approximate world line and momentum to the particle. Let us suppose here that customary space-time in which patterns of events and links can be embedded has been independently defined [3]. A pattern of events and links prior to a given time is a history.

The quantum laws concern two aspects. On the one hand they must determine the intrinsic structure of links and events (for instance the internal wave functions or structure functions of particles). On the other hand they must give probability laws for the formation of specific patterns, including the positions of collision centers. No attempt will be made here to formulate these laws. In the low density example they can be adapted from standard procedure in quantum theory. Let us sketch a strongly simplified version of this which shows some essential aspects. To each type of link α (here a type of particle) we have an associated Hilbert space $\mathcal{H}_\alpha$ and we may consider all the subsequently mentioned spaces as subspaces of the Fock space generated from the $\mathcal{H}_\alpha$ of all types. Consider for simplicity "maximal" events (corresponding to the strongest possible decisions). They specify their backward links completely. If the event has two backward links of types α and β then it selects a specific product vector $\varphi_\alpha \otimes \varphi_\beta \in \mathcal{H}_\alpha \otimes \mathcal{H}_\beta$ and transforms it to a vector in the tensor product space $\mathcal{H}_\gamma \otimes \mathcal{H}_\delta \otimes \cdots$ corresponding to the outgoing channel [4]. This vector is, however, not a product vector but a linear combination of

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large fluctuation but from one of still lower weight.

[3] In a more ambitious analysis one might hope to use the geometry of patterns as a substitute for space-time.

[4] We made the further simplifying assumption that the choice of a specific outgoing channel is included in the characteristics of the event.

such. Its expansion into a sum of product vectors depends on a choice of bases in the factor spaces. The selection of a particular product vector is realized only by the subsequent events since links become established only after both source and target event are realized. A space-like surface not passing through any event defines a "subjective past" consisting of the pattern of all earlier events. Among these events there are saturated ones for which all forward links are absorbed by some other event inside this subjective past and there are others still having free valence links for the formation of future events. To such a subjective past we associate a state which summarizes the probability predictions for possible extensions of the pattern to the future. In our simplified picture the state depends only on the subpattern of the unsaturated past events. As the space-like surface is shifted to the future the associated state changes as new events appear. This change, analogous to the "reduction of the wave packet", corresponds to the transition from a possibility to a fact. Let us illustrate this in the example of the figure in which the wavy line indicates the chosen space-like surface. We are interested in the extension of the past history by the pattern of events 4 and 5 and the newly established links. The temporal order of 1, 2, 3 is irrelevant but it is assumed that no other events of the past can play a role for the events linked to 3. Events 1, 2, 3 fix unit vectors

$$\Phi_1 \in \mathcal{H}_\gamma \otimes \mathcal{H}'_1 \quad ; \quad \Phi_2 \in \mathcal{H}_\delta \otimes \mathcal{H}'_2 \quad ; \quad \Phi_3 \in \mathcal{H}_\alpha \otimes \mathcal{H}_\beta \tag{2}$$

Events 4 and 5 are represented by the rank-1 operators (in Dirac notation)

$$c|\Phi_4\rangle\langle\varphi_\alpha \otimes \varphi_\gamma| \quad , \quad c'|\Phi_5\rangle\langle\varphi_\beta \otimes \varphi_\delta| \tag{3}$$

where the φ_λ are specific unit vectors in the subspaces $\mathcal{H}_\lambda$, ($\lambda = \alpha, \beta, \gamma, \delta$) and Φ_4, Φ_5 unit vectors in the tensor product spaces of the new outgoing channels. The constant c,c' together with the selection of the backward ties i.e. the vectors $|\cdot\rangle$ determine the probability for a single event. Thus the probability for event 4 is obtained by applying the first operator of (3) to $\Phi_1 \otimes \Phi_3$. This yields a vector whose square length gives this probability. To obtain the joint probability for events 4 and 5 we have to apply both operators of (3) to $\Phi_1 \otimes \Phi_2 \otimes \Phi_3$ and square the length of the resulting vector. This joint probability shows correlations even though these events may lie space-like to each other. They are due to the fact that the two events have backward causal links to a common source (event 3). Moreover the vector Φ_3 determined by event 3, does not specify a product vector $\varphi_\alpha \otimes \varphi_\beta$ before both events are realized and thus it is not possible to assign individual "states" to the not yet established links. It is this feature which distinguishes the joint probability for events from the case of classical correlations which result if there is an individual state for each link (possibly unknown) and the correlations are between these states of links. A prime example is the EPR-phenomenon (see below).

The decision for realization of one possible pattern of events is a free choice of nature limited only by the probability assignment. [5] The amount of freedom thus accorded to nature is larger than in the standard view where the experimenter forces nature to decide only on the answer to a proposed question. It must be stressed, however, that also in the standard use of quantum theoretical formalism the element of free choice by nature cannot be eliminated. It is only pushed to the rear by focusing on ensembles instead of individual cases. Thus one may derive from the dynamical law governing the time development of "states" (representing ensembles) that in the case of complex systems the density matrix becomes very fast effectively diagonal in

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[5]One can speculate whether the decision between a large number of alternatives may be decomposed into a sequence of binary decisions, each corresponding to one bit of information. This would appear indicated in a more fundamental approach.
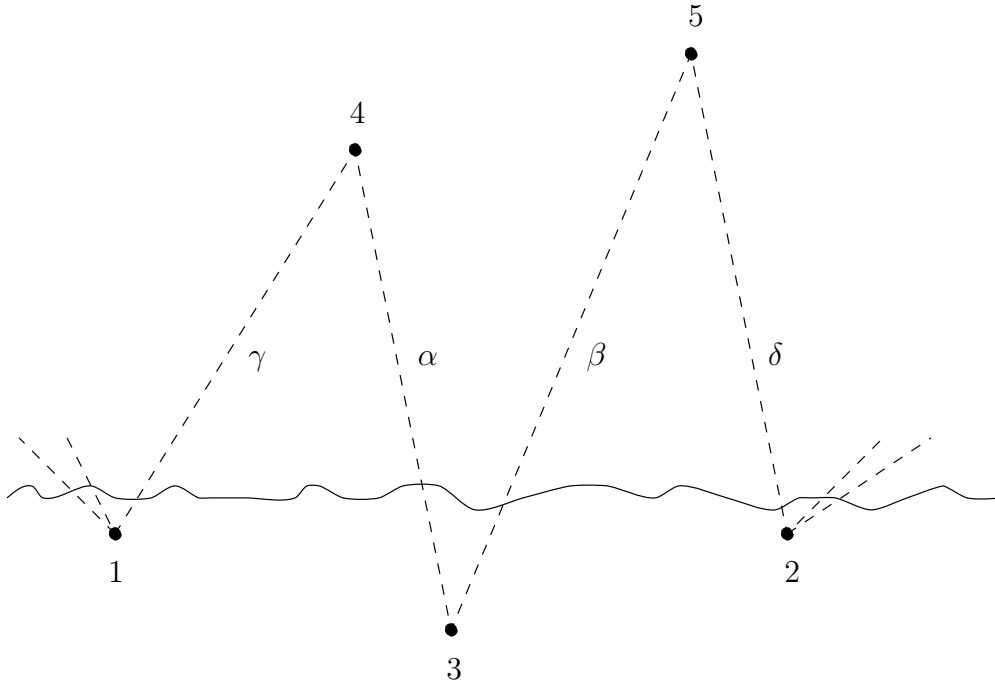
Figure 1: Pattern formation

suitably chosen collective coordinates whatever the initial state may have been. "Effectively" means that in no realistic experiment the off-diagonal terms will play a role ("decoherence"). One concludes then that this final ensemble *may be thought of* as a mixture of subensembles in each of which the collective coordinates have specific values. This is perfectly correct as far as statistical predictions for subsequent measurements are concerned. It does, however, not explain the fact that in each individual case nature has decided for one specific set of values (e.g. the position of a dot on a photographic plate), a decision not controlled by the experimenter and not described by the time development of the density matrix. A striking example of the ambiguities involved in the step from the statistics of an ensemble to conclusions about individual cases will be discussed below. It is interesting to note that Dirac advanced the idea of a free choice of nature in this context in 1927 at the 5th Solvay Congress but was dissuaded by Bohr who emphasized the decisive role of the observer.

3   Comparison with standard procedure.

To compare the degree of compatibility of the scheme with the standard procedure of Quantum Physics let us first look at a process like (1) without subsequent amplification effects. The links to the past are a single μ -meson and a single atom far separated from all other matter. In the conventional treatment we have a Fock space of incoming particles. The initial state is described as a tensor product of two single particle wave functions of the respective center of mass motion (we treat the atom as a single particle). The final state is described as a vector in Fock space resulting from the application of the S-matrix to this tensor product. It is a sum of terms describing the different channels. We write as usual $S = 1 + iT$ and, for a particular final channel (suppressing spin indices)

$$\psi^{out}(p'_1 \ldots p'_n) = \int \tau(p'_1 \ldots p'_n; p_1, p_2)\psi^{in}_1(p_1)\psi^{in}_2(p_2)\delta^4(\sum p'_k - \sum p_k)d\mu(p_1)d\mu(p_2) \quad (4)$$

with $d\mu(p_i) = \delta(p_i^2 - m_i^2)\Theta(p_i^0)d^4p$. Using

$$\delta^4(q) = (2\pi)^{-4}\int \exp ixq d^4x$$

and noting that $\exp ix\sum p'_k$ represents in any channel just the space-time translation by x in the Fock space of outgoing particles (similarly $\exp ix\sum p_k$ for the incoming particles) we may write (4) in vector notation as

$$\Psi^{out} = \int \mathfrak{T}_x\Psi^{in}d^4x, \tag{5}$$

regarding this as a mapping in Fock space where

$$\mathfrak{T}_x = U(x)\mathfrak{T}U(x)^{-1} \tag{6}$$

is the translate by the 4-vector x of an operator $\mathfrak{T}$ whose matrix elements are the functions $\tau(p'_1 \ldots p_k)$. The latter are smooth functions of the momenta apart from the fact that they are needed only on the subspace of momentum conservation and their extension away from this is arbitrary. So we can choose them to be smooth in all momentum arguments and thereby $\mathfrak{T}_x$ becomes a quasilocal operator centered around x. The localization of $\mathfrak{T}_x$ will be poor in the case of long range forces or "weak processes" like soft photon emission or interaction with external fields. Let us leave aside here the problems associated with the existence of massless particles and focus on hard inelastic events. The characteristics of an event include the nature of the backward links i.e. the charges, mass and spin values of the incoming particles and, although they should not include detailed information about forward links since these are fixed only in subsequent events, we may include in our case the choice of a specific final channel and even some rough specification of the momenta of outgoing particles since this concerns mutually exclusive possibilities, provided the isolation is adequate.

In the last section we demanded that we should be able to attribute a rather sharply defined space-time region to the event. This is not yet provided by the sharpness of localization of $\mathfrak{T}_x$ (which corresponds roughly to the range of the interaction) but requires that if we make a cell division in x-space, writing

$$\int \mathfrak{T}_x dx = \sum \mathfrak{T}_k \; ; \quad \mathfrak{T}_k = \int \mathfrak{T}_x g_k(x)dx \; ; \quad \sum g_k(x) = 1 \; ; \; \Psi_k = \mathfrak{T}_k\Psi^{in} \tag{7}$$

with the function g_k having support in the cell k, then, for appropriately chosen cell division, the individual terms Ψ_k may be considered as describing (incoherent) alternatives, one of which is selected by nature in the individual case. By contrast, believing in the absolute validity of the quantum theoretical formalism, one concludes that the phase relation of different Ψ_k can be put in evidence or, in other words, that the needed size of the cells depends strongly on far away circumstances surrounding the process, not only on the event itself (i.e. on the presence of instruments which are far away at the time of the event). To assess the significance of this difference we have to study the statistics of an ensemble of such processes followed by subsequent measurements on the final state. The relevant test experiment is a very precise control of the energy-momentum of all initial and final particles. The assumption of an extension a_ν of the event in the ν-direction implies a limitation in the control of the momentum balance ΔP_ν of order h/a_ν. This raises the question of how precisely the relevant part of past history can be controlled in all samples of the ensemble. Here the following consideration may be instructive. If the overlap region of the wave functions of incoming particles were sufficiently narrow then

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only a single term Ψ_k would occur. But this is usually not the case. Consider the opposite extreme where we take the initial state of the atom in (1) as an equilibrium state in a large vessel so that its position is almost unknown. If β is the inverse temperature the state can be described by a density matrix diagonal in the momentum representation, given by (non relativistically)

$$\langle \mathbf{p}'|\rho|\mathbf{p}\rangle = \delta^3(\mathbf{p}' - \mathbf{p})\exp-\beta\mathbf{p}^2/2m \tag{8}$$

(we have disregarded the normalization). Now we note that precisely the same density matrix also arises as a mixture of Gaussian wave packets, minimal at some time t, with width

$$\lambda = h(\beta/2m)^{\frac{1}{2}} \tag{9}$$

and distributed with uniform density in space and time. Numerically, taking for m the proton mass this gives at a temperature of 1 K a value $\lambda = 2 \cdot 10^{-7}$ cm. Thus it does not make any difference for the statistics of any subsequent experiment whether we assume that the initial state is built up from plane waves or from localized packets of size λ. The origin of this ambiguity is, of course, the non uniqueness of the decomposition of an impure state and we see here that we cannot confine attention to decompositions into mutually orthogonal states because we considered mixtures of packets which are minimal at different times. We are reminded again of the feature that the study of statistics in an ensemble allows widely different pictures for the individual case.

Still, there is no known law of nature which would prevent the control of the momenta of incoming particles and the measurement of the momenta of outgoing particles with arbitrary precision. Such an overall high precision experiment would be, in the standard language, the complementary one to the well known high energy experiments where we see by inspection in the individual case the existence of a collision center from which the tracks of particles emerge. The precision in the definition of this collision center may not be great but it is much sharper than the controlled localization of the incoming particles. At present it must be left to intuition whether one prefers to believe in some fundamental limitation of the accuracy of the "complementary" experiment or in the influence of far separated matter on the extension of the individual collision region.

Let us turn now to patterns of events and links in the low density situation. A link, corresponding to a particle, is mathematically described by an irreducible representation of the total symmetry group which is the direct product of a global gauge group with the Poincare group. The vectors in this representation space give the charge quantum numbers and a wave function for the center of mass motion and spin orientation. The event is described by a *reducible* representation resulting from the tensor product of the irreducible representations associated with the backward links, followed by "quasiprojection" by an operator $\mathfrak{T}_k$. After the event this representation is decomposed again into a sum of tensor products of irreducible representations, each term corresponding to a specific channel of outgoing particles which furnish possible links to subsequent events. A new event is realized by the fusion (tensor product) of such links originating from different past events. We have been careful so far to speak of representations, not of vectors in the representation spaces. The reason is that, in contrast to the simplified picture described in the last section. $\mathfrak{T}_k$ is not a rank 1 operator and we can only include so much information about backward links as corresponds to the characteristics we can attribute to events. These include the approximate momenta determined retrospectively from the location of the source event but no assignment of spin orientation for the links is provided. The τ - functions in (4) do not factor in the variables of outgoing particles. This means that we cannot attribute a specific single particle state to a free valence link and this implies in turn that we

cannot treat the probabilities for the formation of subsequent patterns as a classical stochastic process. While this complication is not very relevant for position patterns in the case where the mean free path is very large compared to the unsharpness of localization of events so that all momenta can be taken as rather well defined though unknown, there is no corresponding mechanism providing a specification of the state of spin orientation of the individual particle. This is demonstrated by the experiments concerning the EPR-effect for spin.

We consider the decay of a spin zero particle into two spin 1/2 particles followed by a measurement of the spin orientation of the two particles with respect to respective directions $\mathbf{e_1}, \mathbf{e_2}$ prescribed by Stern-Gerlach magnets. This may be idealized as the situation pictured in the figure where events 1 and 2 correspond to the setting of the Stern-Gerlach magnets, event 3 to the decay process and events 4 and 5 to the interaction between the decay particles and the two Stern-Gerlach arrangements each allowing only a binary decision whose results are denoted by $+$ or $-$. Since the events 1 and 2 concern the setting of classical apparatus the links γ and δ are already fixed by these events and may be characterized by the directions $\mathbf{e_1}, \mathbf{e_2}$. Disregarding the motion in space and focusing only on the spin, the vector Φ_3 is the unique singlet state in the Hilbert space of 2-particle spin states. If 4 is the event with outcome $+$ then φ_α is realized as the single particle state $\varphi_+(\mathbf{e_1})$ (spin oriented in the $+\mathbf{e_1}$ direction). Since the arrangement is such that we are sure that one of the results $+$ or $-$ must happen the constants c and c' are equal to 1. The joint probabilities are thus given by the well known quantum mechanical expressions.

4   Concluding remarks

The conceptual structure proposed above incorporates the essential message of Quantum Physics and does not seem to be at odds with known experimental findings. The only point of disagreement with the standard mathematical formalism is the assumed relation between events and space-time. The clarification of this issue will demand a considerable amount of theoretical work and possibly also new experiments. One of the reasons in favor of the presented picture is precisely this point. It seems ultimately unsatisfactory to accept space-time as a given arena in which physics has to play. This feature persists even in General Relativity where a 4-dimensional space-time continuum is a priori assumed and only its metric structure depends on the physical situation. In particular, in the absence of all matter and all events there would still remain this continuum, void of any significance. This aspect provided one of the motivations of the author for introducing the notion of "event" as a basic concept with the ultimate aim of understanding space-time geometry as the relations between events [1]. The other motivation was, of course, the desire to separate the laws of Quantum Physics from the presence of an observer [2]. In this respect it appears that theorists discussing quantum processes inside a star or in the early universe necessarily transcend Bohr's epistemology. Usually then the orthodox interpretation is silently ignored but there are some efforts to build a rational bridge from the standard formalism to such areas of physical theory, most prominently the work by Gell-Mann and Hartle [3]. It uses the concept of "consistent histories" introduced by Griffiths [4] and extended by Omnès [5]. For a criticism of this concept see [6]. Its usefulness is restricted by the fact that consistent histories embodying some established fasts (measuring results) are highly non unique. This lead Omnès to the distinction between "reliable properties" and truth.

Still another motivation comes from the following consideration. The general mathematical structure of standard Quantum Theory is extremely flexible. Its connection to physical phenomena depends on our ability to translate the description of circumstances (e.g. experimental

apparatus) to a specification of operators in Hilbert space. Apart from the case of very simple systems the success in this endeavor is due to the fact that for most purposes no precise mathematical specification is needed. Thus, for the treatment of collision processes in Quantum Field Theory it suffices to give a division of "all" observables into subsets which relate to specified space-time regions. However, in addition to this classification of observables one uses the postulate of strict relativistic causality. The consequences of this postulate have been verified by the check of dispersion relations to regions with an extension far below 10^{-13} cm. On the other hand it seems highly unlikely that the construction of an instrument of, say, intrinsic size of 10^{-15} cm and the control of its placement to such an accuracy could be possible even in principle i.e. that we may assume the existence of such *observables*. But is it not unlikely that we can attribute to high energy *events* a localization of this order of magnitude though we have no means of verifying this in the individual dase. Thus the indirect check by means of dispersion relations could be explained by the existence of sharply localized events rather than sharply localized observables.

The realization of a specific result in each individual measurement has been recognized by many authors as a challenge to the theory of measurement which cannot be explained using only the dynamical law of Quantum Theory applied to the interaction of a quantum system with a macroscopic device but needs an additional postulate. In the words of Omnès this is "a law of nature unlike any other". In a series of papers Blanchard and Jadczik suggested a formalism in which irreversibility is introduced in the dynamics of the coupling of a quantum system with a classical one and thereby obtained a (phenomenological) description of this aspect of measurements (see e.g. [7]).

Coming to the evolutionary picture I learned that similar ideas have been presented by A.N. Whitehead already in 1929 [8]. His writings have influenced philosophers and theologians but few if any physicists. In physics D. Finkelstein suggested an approach to the space-time problem based on similar concepts [9]. C.F. v. Weizsäcker tried for many years to draw attention to the fundamental difference between facts as related to the past and possibilities as related to the future and argued that for this reason the statistical statements in physics must always be future directed [10].

To conclude let me express my conviction that for a fundamental physical theory of the future the conceptual structure of standard Quantum Theory is not adequate. This is no basic disagreement with the epistemological analysis of Niels Bohr but the recognition that physical theory always transcends the realm of experience, introducing concepts which can never be directly verified by experience though they may possibly be shown to be incompatible with it.

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